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14. ABSTRACT
Plasmonic and metamaterial devices require high-quality material building blocks with good optical performance, both plasmonic (with the negative real part of the dielectric permittivity) and dielectric, in order to achieve the predicted unusual functionalities and be useful in real world applications. In this project, we have for the first time developed both plasmonic and dielectric materials of the nitrides family that can be grown epitaxially into ultra-thin and ultra-smooth high-quality layers for advanced nanophotonic applications. We have for the first time realized

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Final Report: UNLOCKING NEW PHYSICS AND ENABLING PLASMONIC AND METAMATERIAL DEVICES WITH IMPROVED MATERIALS

ABSTRACT

Plasmonic and metamaterial devices require high-quality material building blocks with good optical performance, both plasmonic (with the negative real part of the dielectric permittivity) and dielectric, in order to achieve the predicted unusual functionalities and be useful in real world applications. In this project, we have for the first time developed both plasmonic and dielectric materials of the nitrides family that can be grown epitaxially into ultra-thin and ultra-smooth high-quality layers for advanced nanophotonic applications. We have for the first time realized plasmonic waveguides using titanium nitride – a gold-like plasmonic ceramic material that has adjustable optical properties, and is robust, low cost and CMOS-compatible. We have showed that a superlattice consisting of titanium nitride as the plasmonic component and aluminum/scandium nitride as the dielectric behaves as an optical hyperbolic metamaterial and exhibits extremely high photonic density-of-states. The outcome of this project is the conclusion that titanium nitride is a very appealing plasmonic material with high performance that could replace and outperform gold in various devices. As a CMOS-compatible material, titanium nitride possesses superior properties compared to noble metals such as adjustable optical properties, high temperature durability, chemical stability, low cost and mechanical hardness that are essential for building nanophotonic devices.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received		Paper
08/06/2013	5.00	U. Guler , G.V. Naik , A. Boltasseva, V.M. Shalaev, A.V. Kildishev. Performance analysis of nitride alternative plasmonic materialsfor localized surface plasmon applications, Applied Physics A, (01 2012): 0. doi:
08/06/2013	6.00	A. Boltasseva, J. B. Khurgin. Reflecting upon the losses in plasmonics and metamaterials, MRS Bulletin, (08 2012): 0. doi:
08/06/2013	7.00	G. V. Naik, V. M. Shalaev, A. Boltasseva. Alternative Plasmonic Materials: Beyond Gold and Silver, ADVANCED MATERIALS, (03 2013): 0. doi:
08/06/2013	8.00	A. V. Kildishev, A. Boltasseva, V. M. Shalaev. Planar Photonics with Metasurfaces, Science, (02 2013): 0. doi:
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Number of Papers published in non peer-reviewed journals:

(c) Presentations

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Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
08/08/2012	3.00	Gururaj Naik, Jeremy Schroeder, Urcan Guler, Xinjgie Ni, Alexander Kildishev, Timothy D. Sands, Alexandra Boltasseva. Metal Nitrides for Plasmonic Applications, CLEO/QELS. 08-MAY-12, . : ,
08/08/2012	4.00	Gururaj Naik, Jongbum Kim, Paul West, Naresh Emani, Alexandra Boltasseva. Oxides and Nitrides as Plasmonic Materials, 3rd International Conference on Metamaterials, Photonic Crystals META 2012. 21-MAR-12, . : ,
TOTAL:		**2**

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
08/06/2013	9.00	B. Saha, G. V. Naik, T. D. Sands, A. Boltasseva. A Titanium Nitride Based Metamaterialfor Applications in the Visible Wavelength Range, Nanometa. 03-JAN-13, . : ,
08/06/2013	10.00	Gururaj V. Naik, Jongbum Kim, Naresh K. Emani, Paul R. West, Alexandra Boltasseva. Plasmonic Metamaterials: Looking beyond Gold and Silver, Metamaterials '2012: The Sixth International Congress onAdvanced Electromagnetic Materials in Microwaves and Optics. 19-SEP-12, . : ,
08/06/2013	11.00	Urcan Guler, Justus C. Ndukaife, Gururaj V. Naik, A. G. Agwu Nnanna, Alexander V. Kildishev, Vladimir M. Shalaev, Alexandra Boltasseva. Local heating with titanium nitride nanoparticles, CLEO/QELS 2013. 09-JUN-13, . : ,
08/06/2013	12.00	Gururaj V. Naik, Bivas Saha, Jing Liu, Sammy M. Saber, Eric Stach, Joseph MK Irudayaraj\, Timothy D. Sands, Vladimir M. Shalaev, Alexandra Boltasseva. A Titanium Nitride based Metamaterial for Applications inthe Visible, CLEO/QELS 2013. 19-JUN-13, . : ,
08/06/2013	13.00	G. V. Naik, J. Kim, U. Guler, N. K. Emani, P. R. West, N. Kinsey, J. C. Ndukaife, A. Boltasseva. Empowering Plasmonics and Metamaterials Technology with New Material Platforms, Frontiers in Nonlinear Physics. 28-JUL-13, . : ,
11/19/2014	24.00	Viktoriia E. Babicheva, Nathaniel Kinsey, Gururaj V. Naik, Marcello Ferrera, Andrei V. Lavrinenko, Vladimir M. Shalaev, Alexandra Boltasseva. Plasmonic Modulator Using CMOS-Compatible Material Platform, 8th International Congress on Advanced Electromagnetic Materials in Microwaves and Optics – Metamaterials 2014. 25-AUG-14, . : ,
11/19/2014	25.00	Nathaniel Kinsey, Marcello Ferrera, Gururaj V. Naik, Alexander V. Kildishev, Vladimir M. Shalaev, Alexandra Boltasseva. Low-Loss Plasmonic Titanium Nitride Strip Waveguides, CLEO 2014. 08-JUN-14, . : ,
11/19/2014	26.00	Jingjing Liu, Urcan Guler, Wei Li, Alexander V. Kildishev, Alexandra Boltasseva, Vladimir M. Shalaev. High-temperature plasmonic thermal emitter for thermophotovotaics, CLEO 2014. 08-JUN-14, . : ,
11/19/2014	27.00	Urcan Guler, Wei Li, Alexandra Boltasseva, Alexander Kildishev, Vladimir M. Shalaev. Titanium Nitride as a Refractory Plasmonic Material forHigh Temperature Applications, CLEO 2014. 08-JUN-14, . : ,

TOTAL: **9**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
08/08/2012	1.00	Gururaj Naik, Jeremy Schroeder, Xingjie Ni, Alexander Kildishev, Timoth D. Sands, Alexandra Boltasseva. Titanium nitride as a plasmonic materialfor visible and near-infrared wavelengths, Optical Materials Express (01 2012)
08/08/2012	2.00	Gururaj Naik, Jingjing Liu, Alexander Kildishev, Vladimir Shalaev, Alexandra Boltasseva. Demonstration of Al:ZnO as a plasmonic componentfor near-infrared metamaterials, Proceedings of the National Academy of Sciences (12 2011)
11/19/2014	19.00	C. Pfeiffer,, N. K. Emani, 'A. M. Shaltout, A. Boltasseva, V. M. Shalaev, A. Grbic. Efficient Light Bending with Isotropic Metamaterial Huygens'Surfaces, Nano Letters (01 2014)
11/19/2014	18.00	Urcan Guler, Alexandra Boltasseva, Vladimir Shalaev. Refractory Plasmonics, Science (03 2014)
11/19/2014	14.00	Bivas Saha, Jing Liu, Sammy M. Saber, Gururaj V. Naik, Eric A. Stach, Joseph M. K. Irudayaraj, Timothy D. Sands, Vladimir M. Shalaev, Alexandra Boltasseva. Epitaxial superlattices with titanium nitride asa plasmonic component for opticalhyperbolic metamaterials, Proceedings National Academy of Sciences (10 2013)
11/19/2014	15.00	Vladimir M. Shalaev, Alexander V. Kildishev, Urcan Guler, Nathaniel Kinsey, Gururaj V. Naik, Alexandra Boltasseva, Wei Li, Jianguo Guan. Refractory Plasmonics with Titanium Nitride: BroadbandMetamaterial Absorber, ADVANCED MATERIALS (10 2014)
11/19/2014	16.00	N. Kinsey, M. Ferrera, G. V. Naik, V. E. Babicheva, V. M. Shalaev, A. Boltasseva. Experimental demonstration of titanium nitrideplasmonic interconnects, Optics Express (04 2014)
11/19/2014	17.00	Jingjing Liu, Gururaj V. Naik, Satoshi Ishii, Clayton DeVault, Alexandra Boltasseva, Vladimir M. Shalaev, Evgenii Narimanov. Optical absorption of hyperbolic metamaterialwith stochastic surfaces, Optics Express (01 2014)
11/19/2014	20.00	Urcan Guler, Justus C. Ndukaife, Gururaj V. Naik, A. G. Agwu Nnanna, Alexander V. Kildishev, Vladimir M. Shalaev, Alexandra Boltasseva. Local Heating with Lithographically Fabricated Plasmonic TitaniumNitride Nanoparticles, Nano Letters (09 2013)
11/19/2014	21.00	Nathaniel Kinsey, Gururaj V. Naik, Marcello Ferrera, Andrei V. Lavrinenko, Vladimir M. Shalaev, Viktoriia E. Babicheva, Alexandra Boltasseva. Towards CMOS-compatible nanophotonics:Ultra-compact modulators using alternativeplasmonic materials, Opt. Express (07 2013)
11/19/2014	22.00	Bivas Saha, Gururaj Naik, Vladimir P. Drachev, Alexandra Boltasseva, Ernesto E. Marinero, Timothy D. Sands. Electronic and optical properties of ScN and (Sc,Mn)N thin filmsdeposited by reactive DC-magnetron sputtering, Journal of Applied Physics (05 2013)
11/19/2014	23.00	Gururaj Naik, Vladimir Shalaev, Alexandra Boltasseva. Alternative Plasmonic Materials: Beyond Gold and Silver, ADVANCED MATERIALS (02 2013)

TOTAL: 12

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Titanium nitride based metanaterial

Patents Awarded

Awards

2014 Member of the Purdue Innovator Hall of Fame, Purdue Research Foundation, Purdue University (Boltasseva, Shalaev)

2014 Joseph W. Goodman Book Writing Award for the book Optical Metamaterials: Fundamentals and Applications; authors: W. Cai and V. Shalaev (Shalaev)

2014 University Faculty Scholar, College of Engineering, Purdue University (Boltasseva)

2014 SPIE travel grant, SPIE Optics and Photonics, San Diego, CA, August 16-21, 2014 (Naresh Emani, Boltasseva's graduate student)

2013 Materials Research Society (MRS) Outstanding Young Investigator Award (Boltasseva)

2013 Institute of Electrical and Electronics Engineers (IEEE) Photonics Society Young Investigator Award (Boltasseva)

2013 IEEE Photonics Society (IPS) 2013 Graduate Student Fellowship (Gururaj Naik, Boltasseva's graduate student)

2013 Outstanding Graduate Student Research Award, College of Engineering, Purdue University (Gururaj Naik, Boltasseva's graduate student)

2012 Nanotechnology Award from UNESCO (Shalaev)

2012 National Academy of Engineering (NAE) U.S. Frontiers of Engineering (FOE) Symposium invitation, September 13-15, 2012, GM Technical Center, Warren, Michigan, USA (invitation-only symposium gathering 78 outstanding engineers under the age of 45) (Boltasseva)

2012 Purdue College of Engineering Early Career Research Award (for 'early excellence with clear potential for future preeminence in research') (Boltasseva)

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Gururaj Naik	0.50	
Nathaniel Kinsey	0.50	
Urcan Guler	0.20	
FTE Equivalent:	**1.20**	
Total Number:	**3**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Gururaj Naik

Total Number: 1

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

please see attached report

Technology Transfer

FINAL REPORT

UNLOCKING NEW PHYSICS AND ENABLING PLASMONIC AND METAMATERIAL DEVICES WITH IMPROVED MATERIALS

Proposal Number: 57981-PH
Agreement Number: W911NF-11-1-0359

Project Period: August 22, 2011 – August 31, 2014

Abstract

Plasmonic and metamaterial devices require high-quality material building blocks with good optical performance, both plasmonic (with the negative real part of the dielectric permittivity) and dielectric, in order to achieve the predicted unusual functionalities and be useful in real world applications. In this project, we have for the first time developed both plasmonic and dielectric materials of the nitrides family that can be grown epitaxially into ultra-thin and ultra-smooth high-quality layers for advanced nanophotonic applications. We have for the first time realized plasmonic waveguides using titanium nitride – a gold-like plasmonic ceramic material that has adjustable optical properties, and is robust, low cost and CMOS-compatible. We have showed that a superlattice consisting of titanium nitride as the plasmonic component and aluminum/scandium nitride as the dielectric behaves as an optical hyperbolic metamaterial and exhibits extremely high photonic density-of-states. The outcome of this project is the conclusion that titanium nitride is a very appealing plasmonic material with high performance that could replace and outperform gold in various devices. As a CMOS-compatible material, titanium nitride possesses superior properties compared to noble metals such as adjustable optical properties, high temperature durability, chemical stability, low cost and mechanical hardness that are essential for building nanophotonic devices.

UNLOCKING NEW PHYSICS AND ENABLING PLASMONIC AND METAMATERIAL DEVICES WITH IMPROVED MATERIALS

(1) Summary

The search for new plasmonic materials with better and more versatile optical properties than noble metals (such as low loss, tunability, durability, easier fabrication and integration capabilities) could lead to real-life applications of plasmonics and metamaterials as well as demonstrations of new phenomena. In this project, we have built upon our pioneering results in the area of new plasmonic materials and showed that one class of plasmonic ceramics, namely, transition metal nitrides, perform as good plasmonic materials in the visible and near-infrared wavelength regions and have optical properties similar to those of gold. Titanium nitride (TiN) can replace noble metals in plasmonic and metamaterial devices and is CMOS-compatible, mechanically tough, and thermally stable. We have developed fabrication approach for growing ultra-thin (few nm) films of titanium nitride with controlled optical properties (such as plasma frequency) and epitaxial quality for applications in plasmonics and metamaterials. In this project, we have demonstrated the excitation of surface plasmon polaritons on epitaxial TiN thin films and conducted detailed comparative studies of the performance of various plasmonic and metamaterial structures with TiN as the plasmonic component. We have also showed that titanium nitride could provide performance that is comparable to that of gold for various plasmonic applications and can significantly outperform gold and silver for transformation-optics and metamaterial applications. We have for the first time realized titanium nitride plasmonic waveguides with performance comparable to that of gold interconnects. The other major result obtained during the funded project is the first-time realization of a new type of hyperbolic metamaterials (HMMs) using TiN as the plasmonic component. We realized a new type of multilayered metamaterials that are truly binary nitride superlattice systems consisting of ultra-thin (down to 5nm), smooth, epitaxial layers of TiN and a lattice-matched dielectric ((Al,Sc)N). We have showed that TiN as the plasmonic material enables the long-awaited shift from previously demonstrated lossy HMMs based on thicker, polycrystalline layers of metals and dielectrics to high-performance superlattice HMMs consisting of ultra-thin layers that are now unlocking the full range of unusual HMM properties. For example, HMMs have been shown to exhibit extremely high, broadband photonic densities of states (PDOS), which are useful in quantum photonics applications. Our studies revealed that TiN superlattice HMMs provide a higher PDOS enhancement than gold- or silver-based HMMs.

(2) Introduction and statement of the problem studied

(2.1) New plasmonic materials

In recent years, the emerging areas of nanophotonics and, in particular, plasmonics and metamaterials, have seen an explosion of novel ideas. The field of *plasmonics* – or optics based on metals – has long been seen as a promising technology that can uniquely combine the advantages of the nanometer-scale (but relatively slow) electronics and ultra-fast (but µm-scale) photonics, thus enabling an increased synergy between these two major technologies [1-6]. The application domain of plasmonics has expanded greatly with the introduction of *optical metamaterials* (MMs) [7-10]. These engineered structures with smartly designed, nanostructured building blocks enable devices with unique optical properties unattainable with "natural" materials [7-10]. The astonishing designs and demonstrations range from nano-optics with waveguiding and focusing of light at the nanoscale, subwavelength-resolution imaging, invisibility cloaking and extreme light concentrators to novel sensors and quantum information applications [8-10]. However, those devices face a challenge - the high losses that dampen the oscillations of free electrons coupled to photons and that are known as *surface plasmons* (SPs) in constituent metal building blocks.

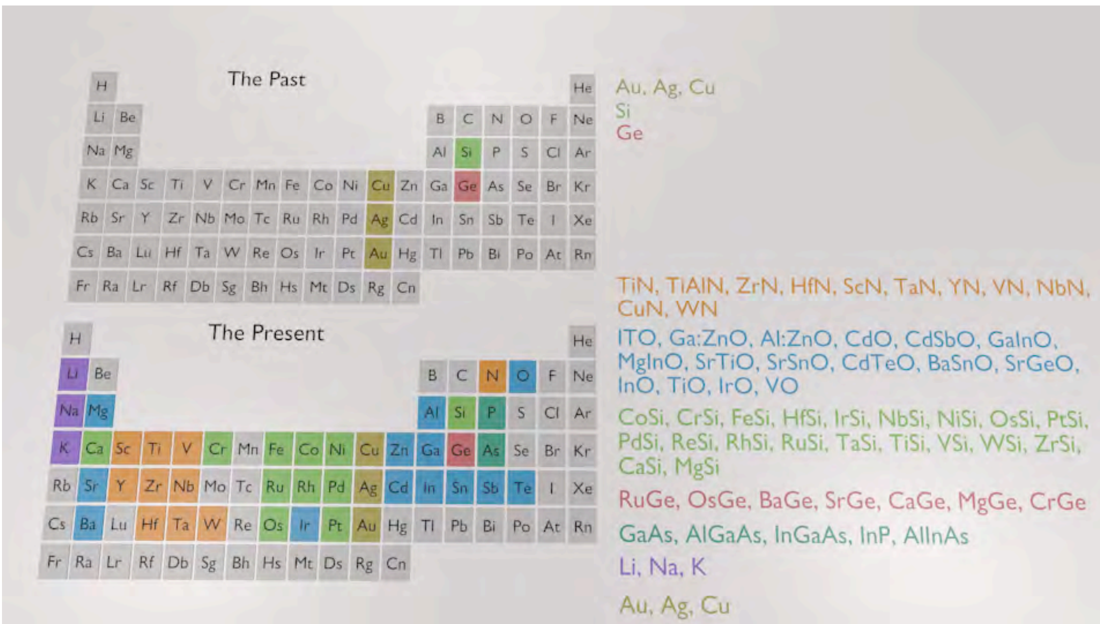

Fig. 1. Periodic table perspective shows that in the optical range only gold, silver and copper elements were widely used before. Nowadays there are many elements that could enter future plasmonic devices as constituent materials supporting surface plasmon excitations. These new materials could offer better device performance and new functionalities such as tunability and switching combined with low cost, fabrication and integration advantages.

The SPs enable a main missionary objective of plasmonics - to route and manipulate light at the nanoscale [1-6] - and the unusual MM properties. Excessive losses in the visible (VIS) and near-infrared (NIR) regions, even in the best conductors like noble metals (silver and gold), threaten to render plasmonic and MM devices nearly useless. Moreover, the properties of metals cannot be tuned or adjusted; and metal building blocks pose grand challenges in fabrication and integration with the established semiconductor processing, thus restricting plasmonic and MM devices to the proof-of-concept stage only. With the design principles and fabrication methods [11;12] well established, the search for new materials is of great importance [13]. The discovery of new plasmonic materials (Fig. 1) that have a negative real part of permittivity that can be tailored/adjusted and an imaginary part (material loss) as small as possible [13-18] is expected revolutionize the field of nanoscale photonics.

In this project, we have built upon our discovery of materials that offer low loss and tunability in their optical properties as well as semiconductor compatibility [18 and references therein] thus addressing the need in the fields of plasmonics and optical metamaterials to overcome problems associated with the use of metals as constituent materials. We pioneered the recent search for new plasmonic materials [13], defining new intermediate carrier density materials such as transparent conducting oxides (TCOs) (indium-tin-oxide, ITO, and zinc oxide doped with aluminum, AZO, or gallium, GZO) and transition metal nitrides (TMNs) (TiN, ZrN and other) as the best candidates with low loss, extraordinary tuning capabilities, and compatibility with standard semiconductor technology [16-19].

(2.2) High-performance MMs realization

Hyperbolic metamaterials (HMMs) have been shown to exhibit exotic optical properties [10, 11, 5.1.2, 5.1.3, 5.2.11 and references therein], including extremely high broadband photonic densities of states (PDOS), which are useful in quantum plasmonics applications. The realization of optical HMM devices is hindered by the fact that metals (used as HMM subwavelength building blocks) with their large negative permittivity and high losses in the optical frequency range are detrimental to HMM performance. Also, it is difficult to pattern noble metals into ultra-thin films or high-aspect ratio nanowires necessary for building HMMs. There are two methods of realizing HMMs: embedding metal nanowires in a dielectric host and stacking alternating planar layers of metal and dielectric. Among the two approaches to build HMMs, planar HMMs are important from a technological point-of-view because they can be easily integrated into existing processing lines that use planar fabrication technology. In multilayered HMMs, in order to achieve a significant enhancement of the PDOS, the individual HMM layers need to be as thin as possible (PDOS in a HMM is inversely related to the cube of the layer thickness). Noble metal films such as gold or silver currently used to create HMM structures cannot be patterned into ultra-thin layers without compromising their quality, resulting in additional losses. Thus, the realization of metal-based HMMs with deep subwavelength layers and good optical performance is extremely challenging. Moreover, neither gold nor silver offers thermal stability and silicon CMOS compatibility required for the technology-driven applications. Thus, new constituent materials that can provide much better performance, new functionalities, and switching capabilities in previously unavailable designs are needed. As another crucial contribution, new materials could offer *epitaxial growth* of ultra-thin layers that dramatically widens both the function and integration horizons for HMMs. Building upon our prior studies of TiN as a plasmonic material that resembles gold in its optical properties, we have studied the usage of TiN for HMMs operating in the visible frequency range. The epitaxially grown, heterogeneous nitride superlattice system shows unparalleled characteristics in terms of structural quality and optical properties.

(3) Summary of the most important results

(3.1) Comparative studies of new plasmonic materials

In this project we conducted detailed comparative studies of the performance of transition metal nitrides for various applications [18, 5.1.4, 5.1.6, 5.2.1, 5.2.3, 5.2.8-5.2.10]. For a SP resonance in a plasmonic nanoparticle, a simple approximation comparing the ratio of the enhanced field intensity on the surface of a spherical nanoparticle to the intensity of the incident field is shown in Fig. 2 for nanoparticles made of different materials at two different wavelengths, 500 and 1700 nm (selected for illustrative purposes) (based on data reported in [18]). Titanium nitride and zirconium nitride have performances similar to that of Au and exhibit localized SP resonance modes in the visible part of the spectrum. In particular, titanium nitride could be of significant interest for biological applications, because TiN is biocompatible and its SP resonance mode lies in the biological transparency window (700–1000 nm) (also known as therapeutic window, it defines the range of wavelengths where light has its maximum depth of penetration in tissue) [5.2.8].

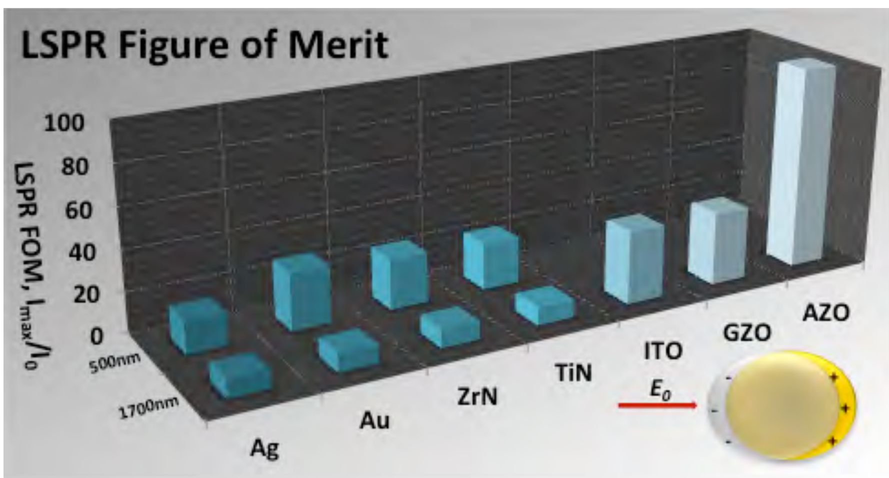

Fig. 2. Comparison of the figures of merit (FOMs) for localized surface plasmon resonance (LSPR): the maximum field intensity enhancement on the surface of a spherical nanoparticle (inset) of the plasmonic material computed from quasistatic approximations[18] at two wavelengths, 500 and 1700 nm. The nanoparticles are assumed to be in a host of refractive index 1.33. The same order of magnitude (or even higher) can be obtained for the enhanced field in new plasmonic materials compared to noble metals. Note: I_{max}, is the maximum field intensity on the surface of a spherical nanoparticle; I_0, is the intensity of the incident field; E_0, indicates the incident field; Columns are colour graded for illustrative purposes.

The second example is a class of hyperbolic metamaterials [5.1.2, 5.1.3, 5.2.11 and references therein]. The recent discovery of the enhancement of the photonic density of states within a broad bandwidth in hyperbolic metamaterials could revolutionize PDOS engineering, potentially enabling light sources with dramatically increased photon extraction efficiency. However, metals with their large negative permittivity and high optical losses limit the metamaterial performance. Moreover, in order to achieve high PDOS, the individual metamaterial layers need to be as thin as possible. Noble metal films cannot be patterned into ultra-thin layers without compromising their quality. Thus, realization of multilayered metamaterials with deep subwavelength layers and good performance based on metals is extremely challenging. To conduct a comparative study of different materials for hyperbolic metamaterials applications, a performance metric, a FOM, defined as the ratio of the real and imaginary parts of the wave vector perpendicular to the layers, is a good indicator of the performance (Fig. 3). In the visible and NIR ranges, alternative plasmonic materials clearly outperform noble metals by orders of magnitude (Fig. 3). We have previously demonstrated the first metal-free hyperbolic metamaterial that exhibits negative refraction in the NIR region by replacing conventional metal layers with highly doped ZnO and combining with dielectric ZnO layers [5.2.11]. Recently, we have pursued the transition to a completely new concept of creating layered metamaterials. This can be compared to heterostructure growth used to make semiconductor devices. Instead of creating metamaterials by assembling layers by usual means—depositing polycrystalline layers of metal and dielectric—now, for the first time, a layered metamaterial is grown as a superlattice [5.1.2, 5.2.6].

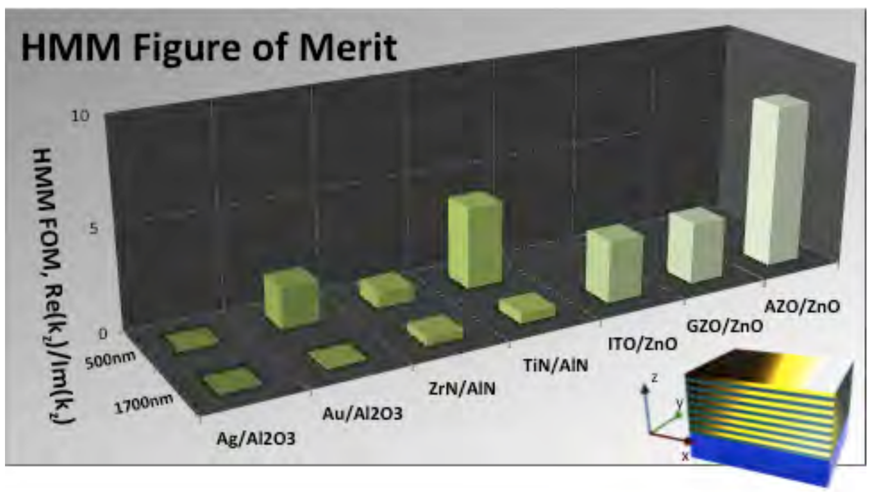

Fig. 3. The figure of merit of hyperbolic metamaterials (HMM) (inset), defined as the ratio of the real (Re(k_z)) and imaginary (Im(k_z)) parts of the wave vector perpendicular to the layers, along the *z* direction for two wavelengths, 500 and 1700 nm. The calculations are for planar alternating layers of metal/dielectric layers formed by different pairs of materials. In the optical range, alternative plasmonic materials clearly outperform noble metals by orders of magnitude. Columns are colour graded for illustrative purposes.

(3.2) Plasmonic TiN waveguides

To combat the significant losses associated with plasmonic structures, the long-range surface plasmon polariton (LR-SPP) mode has received significant attention [5,19, 5.1.1, 5.1.5 and references therein]. Using this mode, losses on the order of 0.5 dB/mm have been achieved in the strip geometry for noble metals. However, for practical devices, alternative materials must be considered. A graph of the propagation length for the transition metal nitrides which are metallic at 1.55 µm is shown in Fig. 4. TiN is able to achieve a propagation length of approximately 6 mm. Similarly structured TiN waveguides on sapphire covered with index oil ($n_{oil} = n_{sapphire} = 1.746$) have experimentally demonstrated propagation lengths of 5.5 mm with a mode size of 8 µm, comparing well to gold waveguides which have a 8.7 mm propagation length for a mode size of 20 μm in a polymer ($n_{polymer}$ = 1.535). An image of the modal output of the TiN waveguides on sapphire is shown in Fig. 4(b) [5.1.1].

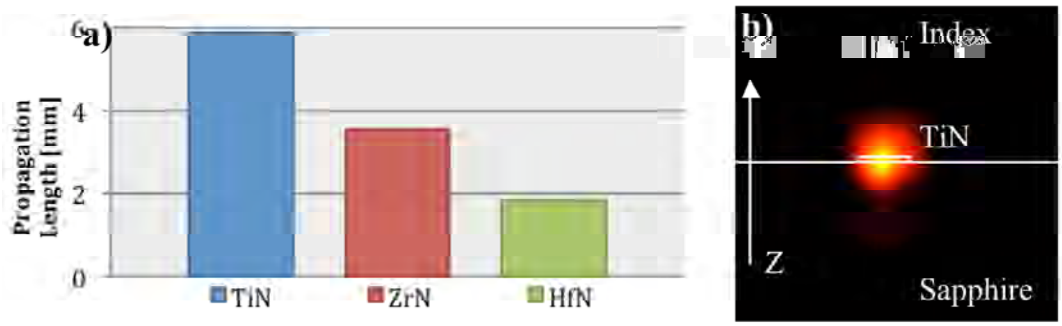

Fig. 4. a) Propagation length (1/e decay of the power) for transition metal nitrides at 1.55 μm. The structure was simulated in COMSOL Multiphysics® in a host index of n = 1.75 for a strip width of 8 μm and a thickness of 10 nm. b) Experimentally measured modal profile of the TiN plasmonic waveguide achieving 5.5 mm propagation length on sapphire.

(3.3) First epitaxial metal/dielectric superlattices using TiN as the plasmonic material

In this project, we developed an approach to grow alternating layers of TiN and a low loss dielectric epitaxially [5.1.2, 5.2.6]. In order to build an *epitaxial metal/dielectric superlattice* consisting of TiN as a plasmonic material, a dielectric that has the same crystal structure (rocksalt) and lattice constant (4.24 Å) as TiN should be selected. AlN is a low-loss dielectric in the visible spectral range that can be engineered to grow epitaxially on TiN. However, the critical thickness for stabilizing the cubic phase of AlN on TiN/AlN superlattices is less than 2.5 nm which is not suitable for practical applications. We have stabilized the cubic phase of $Al_xSc_{1-x}N$ by alloying AlN with scandium nitride (ScN), to deposit cubic TiN/(Al,Sc)N superlattices. An aluminium concentration of 72% in $Al_xSc_{1-x}N$ (estimated with Rutherford backscattering spectrometry) was found to be suitably lattice matched with TiN.

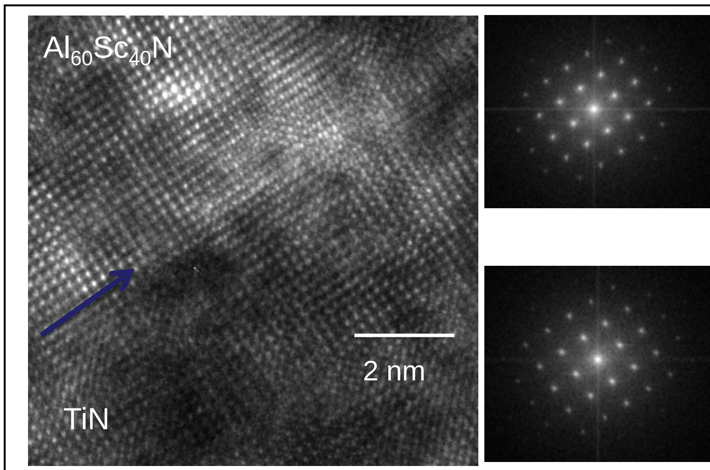

Fig. 5. High resolution TEM image showing the interface of TiN and (Al,Sc)N in the superlattice together with the fast Fourier transforms corresponding to the diffractograms on the either sides of the interface.

Superlattices consisting of TiN and $Al_{0.72}Sc_{0.28}N$ alternating layers of equal thickness were grown on [001] MgO substrates. The X-ray diffraction analysis along with the high resolution transmission electron microscopic images (Fig. 5) suggest that the superlattices grow with a (001) orientation on the [001] MgO substrates and that both

TiN and (Al,Sc)N have the same lattice constants. We also showed that metal/dielectric interfaces are sharp and abrupt as layers as thin as 2nm can be grown.

(3.4) TiN/(Al,Sc)N superlattice HMM

Since the superlattice is composed of layers much smaller than the wavelength of light, it can be approximated by a uniaxial anisotropic effective medium [5.1.2, 5.1.3]. In the 540-600 nm range, the dispersion of the fabricated HMMs is transverse-positive or type-1, which is useful in building devices such as a hyperlens. For wavelengths longer than 650 nm, the dispersion is transverse-negative or type-2, which is useful for applications where PDOS enhancement is desirable.

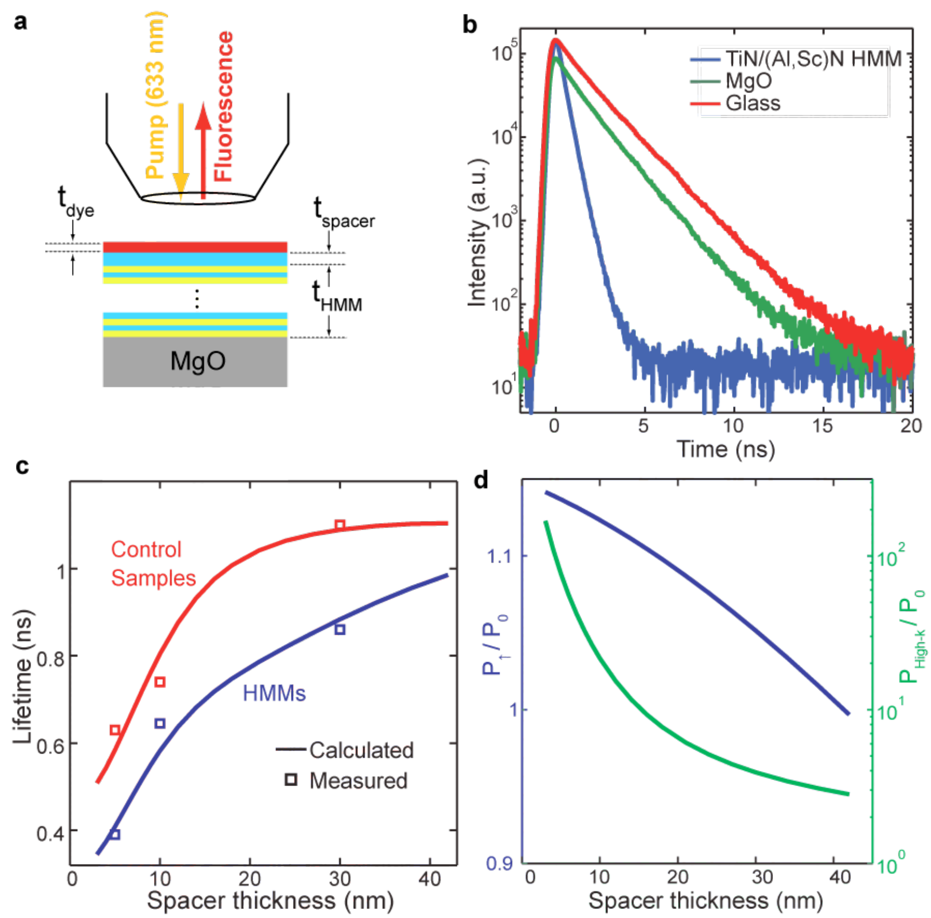

Fig. 6. Experiments to probe the photonic density of states of a HMM: (a) The schematic showing the sample geometry and the experiment configuration. (b) Measured spontaneous emission vs. time profiles from dye molecules placed on top of TiN/(Al,Sc)N superlattice with individual layers 10 nm thick, bare MgO and bare glass substrates. (c) Lifetimes of dye molecules on TiN/(Al,Sc)N HMMs or 10 nm TiN film (control) as a function of the distance from the top metal surface of the sample. The HMMs are composed of 24 layers each being 10 nm thick. The dye layer is separated from HMM/control sample surface by (Al,Sc)N spacer layer. The calculated emitter lifetimes (solid line) for different spacer layer thickness were fit to the measured values (squares). (d) Calculated normalized power (see supporting information) radiated from the emitter into low-*k* modes that propagate in the upper-half-plane (left axis) and high-*k* modes that propagate only in the HMM (right axis). Note significant (about two orders of magnitude) increase of the power radiated into high-*k* modes with the decreasing spacer thickness.

The losses in the fabricated HMMs were low enough to measure more than 15% transmittance from a 160 nm thick superlattice at approximately a 600 nm wavelength

[5.1.2]. It should be noted that a 160 nm thick HMM built from similar alternating layers of noble metals (if one could make them continuous at such a small thickness) and any dielectric would have less than 1% transmittance.

The small losses and ultra-thin layers are expected to significantly increase the enhancement of PDOS in the superlattice HMMs. We conducted experimental studies of the PDOS enhancement in the superlattice HMMs. We achieved a good agreement between calculated and measured lifetimes for the emitters placed on top of HMMs confirming the enhancement of PDOS provided by TiN/(Al,Sc)N HMMs [5.1.2] (Fig. 6a). Fig. 6b shows the lifetime measurements on TiN/(Al,Sc)N HMM with 10 nm thick individual layers, consisting of 12 pairs of layers plus an additional spacer layer on top. The spacer layer was made of the same dielectric, (Al,Sc)N, used in the HMM. Three such HMMs with three different spacer layer thicknesses were fabricated. Approximately an 11 nm thick layer containing dispersed dye molecules was spin-coated on top of the HMMs. The results of the lifetime measurements are shown in Fig. 6c. The HMM with the thinnest spacer layer of 5 nm shows the smallest lifetime while the HMMs with the thicker spacer layers (10 and 30 nm) show much larger lifetimes. This is because the emitter, which is closer the surface of HMM, couples light more effectively into the HMM from a very broad range of wavevectors (k) that includes not only those wavevectors supported by vacuum, but also those with significantly higher wavevectors (high-k modes). Hence, more radiation channels are available for the emitter to radiate into the HMM propagating high-k modes, which reduces the lifetime. In order to predict the lifetime of the dye molecules placed on the top of HMM with different spacer thicknesses, we employ Local Density of States (LDOS) calculations (see supporting information) [5.1.2]. The good agreement between calculated and measured lifetimes confirm the enhancement of PDOS provided by TiN/(Al,Sc)N HMMs [5.1.2]. In order to assess the role of SPs in enhancing the PDOS, we prepared control samples consisting of 10 nm TiN films on MgO substrates with a top (Al,Sc)N spacer layer. The spacer layer was 5, 10 and 30 nm thick in three different samples. The dye layer was spin coated on top of these control samples by exactly the same protocol as employed on the HMMs. The results of lifetime measurements on these control samples are also shown in Fig. 6c. The control samples provide enhancement in the emission rate by nearly two times (in comparison to emission rate on bare glass) due to excitation of SPs at the top and bottom interfaces of the TiN film. However, the emission rate enhancements observed in the control samples are smaller than those provided by HMMs by approximately two times. It must be noted that lifetime reduction by 2 times implies nearly 20 times higher PDOS because the quantum yield of the emitter is nearly 10%. Thus, the PDOS in HMMs is enhanced significantly compared to the control samples. The high-k channels into which the dye molecule emits are confined only to the HMM because no other surrounding medium supports them. Hence, these photons do not reach the detector, causing a reduction in the apparent quantum yield. When the spacer thickness is small, the emitters emit most of their power into high-k modes in the HMM (note, for example, the tenfold increase in the power emitted into high-k modes when the spacer thickness is reduced from 40 nm to below 20 nm, see Fig. 6d). The extremely small apparent quantum yield is a clear indication that the emitters are effectively probing the high PDOS of the HMMs [5.1.2].

(3.5) Conclusion

In conclusion, we showed that the usage of titanium nitride in plasmonic structures and hyperbolic metamaterials instead of noble metals paves the way towards the realization of practical plasmonic and MM devices that have low loss, controllable properties and are CMOS- and bio-compatible, and thermally stable. Titanium nitride as the plasmonic material enables novel CMOS-compatible interconnect and the long-awaited leap from previously demonstrated lossy HMMs based on thick, polycrystalline layers of metals and dielectrics to high-performance, truly binary superlattice HMMs consisting of ultra-thin, smooth, epitaxial layers that could ultimately unlock the full range of unusual properties of hyperbolic metamaterials. Our study clearly demonstrates the benefits of replacing noble metals by TiN in layered HMMs. A more important consequence is that TiN could boost the performance in many more classes of plasmonic and metamaterial devices. The developed approach can be applied to other areas of plasmonics and optical metamaterials and enable first CMOS-compatible plasmonic interconnects and circuits as well as improved imaging, sensing, light harvesting and medical devices utilizing titanium nitride with its adjustable properties, bio-compatibly, chemical and thermal stability. High performance, low loss TiN-based metamaterials could also lead to a new generation of light sources and devices for quantum optical technologies.

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(5) Appendices

(5.1) Major results reported

5.1.1. N. Kinsey, M. Ferrera, G. V. Naik, V. E. Babicheva, V. M. Shalaev, A. Boltasseva, “Experimental demonstration of titanium nitride plasmonic interconnects,” *Optics Express* 22 (10), 12238-12247, DOI:10.1364/OE.22.012238 (May 19 2014)

5.1.2. G. V. Naik, B. Saha, J. Liu, S. M. Saber, E. Stach, J. MK Irudayaraj, T. D. Sands, V. M. Shalaev, A. Boltasseva, “Epitaxial superlattices with titanium nitride as a plasmonic component for optical hyperbolic metamaterials,” *Proceedings of the National Academy of Sciences*, doi: 10.1073/pnas.1319446111 111 (21), 7546-7551 (May 2014)

5.1.3. J. Liu, G. V. Naik, S. Ishii, C. DeVault, A. Boltasseva, V. M. Shalaev, E. Narimanov, “Optical Absorption of Hyperbolic Metamaterial,” *Optics Express* 22 (80), 8893-8901, DOI:10.1364/OE.22.008893 (April 21 2014)

5.1.4. A. Boltasseva, “Empowering plasmonics and metamaterials technology with new material platforms,” *MRS Bulletin*, volume 39, DOI: 10.1557/mrs.2014.91 (May 2014)

5.1.5. V. E. Babicheva, N. Kinsey, G. V. Naik, M. Ferrera, A. V. Lavrinenko, V. M. Shalaev, A. Boltasseva, “Towards CMOS-compatible nanophotonics: Ultra-compact modulators using alternative plasmonic materials,” *Optics Express* 21 (22), 27326-27336, DOI:10.1364/OE.21.027326 (4 November 2013)

5.1.6. G. V. Naik, J. L. Schroeder, X. Ni, A. V. Kildishev, T. D. Sands, A. Boltasseva, “Titanium nitride as a plasmonic material for visible and near-infrared wavelengths,” *Optical Materials Express* 2, 478-489 (April 2012) (**Top OMEx download since April 2012*, highlighted in OSA press release and key industry media outlets Science Daily, NSF Science 360, Red Orbit, Photonics.com, April 2012*)

(5.2) Publications related to efforts supported by the grant *in part*

5.2.1. U. Guler, V. M. Shalaev, A. Boltasseva, "Nanoparticle Plasmonics: Going Practical with Transition Metal Nitrides," *Materials Today* (in press, 2014)

5.2.2. W. Li, U. Guler, N. Kinsey, G. V. Naik, A. Boltasseva, J. Guan, V. M. Shalaev, A. V. Kildishev, "Refractory Plasmonics with Titanium Nitride: Broadband Metamaterial Absorber," *Advanced Materials*, DOI: 10.1002/adma.201401874 (October, 2014)

5.2.3. U. Guler, A. Boltasseva, V. M. Shalaev, "Refractory Plasmonics," *Science*, 344 (6181), 263-264, DOI: 10.1126/science.1252722 (April 18 2014)

5.2.4. C. Pfeiffer, N. K. Emani, A. M. Shaltout, A. Boltasseva, V. M. Shalaev, A. Grbic, "Efficient Light Bending with Isotropic Huygens' Surfaces," *Nano Letters* 14, 2491-2497, dx.doi.org/10.1021/nl5001746 (April 1 2014)

5.2.5. U. Guler, J. C. Ndukaife, G. V. Naik, A. G. A. Nnanna, A. V. Kildishev, V. M. Shalaev, A. Boltasseva, "Local Heating with Lithographically Fabricated Plasmonic Titanium Nitride Nanoparticles," *Nano Letters* 13 (12), 6078–6083 DOI: 10.1021/nl4033457 (November 26, 2013)

5.2.6. B. Saha, G. Naik, V. P. Drachev, A. Boltasseva, E. E. Marinero, T. D. Sands, "Electronic and optical properties of ScN and (Sc,Mn)N thin films deposited by reactive DC-magnetron sputtering", *Journal of Applied Physics* 114 (6), 063519, DOI: 10.1063/1.4817715 (August 14 2013)

5.2.7. A. V. Kildishev, A. Boltasseva, V. M. Shalaev, "Planar Photonics with Metasurfaces," *Science* 339, 1232009-1-6 (2013)

5.2.8. G. V. Naik, V. M. Shalaev, A. Boltasseva, "Alternative Plasmonic Materials: Beyond Gold and Silver," *Advanced Materials*, DOI: 10.1002/adma.201205076 (2013)

5.2.9. J. B. Khurgin and A. Boltasseva, "Reflecting upon the losses in plasmonics and metamaterials," *MRS Bulletin* 37, no. 8, 768-779 (2012) (*invited*)

5.2.10. U. Guler, G. V. Naik, A. Boltasseva, V. M. Shalaev, A. V. Kildishev, "Performance analysis of nitride alternative plasmonic materials for localized surface plasmon applications," *Applied Physics B* 107, 285-291 (2012)

5.2.11. G.V. Naik, J. Liu, A. V. Kildishev, V. M. Shalaev, A. Boltasseva, "Demonstration of Al:ZnO as a plasmonic component of near-infrared metamaterials," *Proceedings of the National Academy of Sciences* 109, 8834-8838 (2012)

Conference proceedings

- V. Babicheva, N. Kinsey, G. Naik, M. Ferrera, A. Lavrinenko, V. M. Shalaev, A. Boltasseva, "Plasmonic Modulator Using CMOS-Compatible Material Platform", 8th

International Congress on Advanced Electromagnetic Materials in Microwaves and Optics – Metamaterials 2014, 3 pages, Copenhagen, Denmark, 25-30 August 2014
- N. Kinsey, M. Ferrera, G. Naik, A. Kildishev, V. M. Shalaev, A. Boltasseva, “Low-Loss Plasmonic Titanium Nitride Strip Waveguides,” contribution STu1M.1, CLEO 2014, San Jose, CA, USA, June 8-13, 2014
- J. Liu, U. Guler, W. Li, A. Kildishev, A. Boltasseva, V. M. Shalaev, “High-temperature plasmonic thermal emitter for thermo-photovotaics,” contribution FM4C.5, 2 pages, CLEO 2014, San Jose, CA, USA, June 8-13, 2014
- U. Guler, A. Kildishev, A. Boltasseva, V. M. Shalaev, “Titanium nitride nanoparticles for therapeutic applications,” contribution FM1K.4, 2 pages, CLEO 2014, San Jose, CA, USA, June 8-13, 2014
- U. Guler, Wei Li, A. Boltasseva, A. Kildishev, V. M. Shalaev, “Titanium Nitride as a Refractory Plasmonic Material for High Temperature Applications,” contribution FM4C.8, 2 pages, CLEO 2014, San Jose, CA, USA, June 8-13, 2014
- G. V. Naik, B. Saha, T. D. Sands, S. M. Saber, E. Stach, V. M. Shalaev, A. Boltasseva, “A Titanium Nitride-based Hyperbolic Metamaterial in the Visible and Infrared,” 7th International Congress on Advanced Electromagnetic Materials in Microwaves and Optics – Metamaterials 2013 proceedings, 3 pages, Bordeaux, France, September 16-21, 2013
- G. V. Naik, J. Kim, U. Guler, N. K. Emani, P. R. West, N. Kinsey, J. C. Ndukaife, A. Boltasseva, ''Empowering Plasmonics and Metamaterials Technology with New Material Platforms,'' Frontiers of Nonlinear Physics (FNP'13) Proceedings, p. 257, 1 page, Nizhny Novgorod-Tchaikovsky, Russia, July 28-August 2, 2013
- G. V. Naik, B. Saha, J. Liu, S. Saber, E. Stach, T. D. Sands, V. Shalaev, A. Boltasseva, ''A Titanium Nitride based Metamaterial for Applications in the Visible,'' contribution QTu3A.7, 2 pages, CLEO/QELS 2013, San Jose, CA, USA, June 9-14, 2013
- U. Guler, J. Ndukaife, G. V. Naik, A. G. Agwu Nnanna, A. Kildishev, V. Shalaev, A. Boltasseva, ''Local heating with titanium nitride nanoparticles,'' contribution QTu1A.2, CLEO/QELS 2013, San Jose, CA, USA, June 9-14, 2013
- G. V. Naik, B. Saha, T. D. Sands, A. Boltasseva, ''A titanium nitride based metamaterial for applications in the visible wavelength range,'' 4th International Topical Meeting on Nanophotonics and Metamaterials (NANOMETA 2013), Seefeld, Austria, January 2-6, 2013, contribution # 169, 1 page
- G. V. Naik, J. Kim, N. K. Emani, P. R. West, A. Boltasseva, ''Plasmonic metamaterials: Looking beyond gold and silver,'' 6th International Congress on Advanced Electromagnetic Materials in Microwaves and Optics: Metamaterials 2012, St. Petersburg, Russia, September 17-22, 2012, Metamaterials 2012 proceedings, 3 pages
- U. Guler, G. Naik, A. Boltasseva, V. Shalaev, A. Kildishev, “Nitrides as alternative materials for localized surface plasmon applications,“ FTh4A.2, 2 pages, 2012 Frontiers in Optics, Rochester, New York, October 14-18, 2012
- G. Naik, J. Liu, A. Kildishev, V. Shalaev, A. Boltasseva, “All-semiconductor metamaterial with negative refraction in the near-infrared,” CLEO/QELS 2012 Proceedings, QTh1A.1, 2 pages

Related conference contributions and talks

- (Invited) N. Kinsey, U. Guler, J. Kim, G. V. Naik, *V. M. Shalaev, A. Boltasseva*, "Developing ceramic materials for practical plasmonics," SPIE Optics and Photonics, Metamaterials, Metadevices, and Metasystems 2014 conference, paper # 9160-52, San Diego, California, USA, August 17-21, 2014
- (Invited) N. Kinsey, M. Ferrera, V. Babicheva, G. V. Naik, A. V. Kildishev, *V. M. Shalaev, A. Boltasseva*, "CMOS Integrated Plasmonics: Interconnects and Modulators," SPIE Optics and Photonics, Active Photonic Materials VI conference, paper # 9162-18, San Diego, California, USA, August 17-21, 2014
- (Invited) *E. Narimanov*, "Photonic hyper-crystals", paper 9160-13, SPIE Optics and Photonics - 2014, San Diego, August 17 - 21, 2014
- T. Tumkur, J. K. Kitur, L. Gu, G. Zhu, C. E. Bonner, V. A Podolskiy, *E. E. Narimanov*, M. A. Noginov, Controlling physical phenomena with hyperbolic metamaterials, 2014 Summer Topicals Meeting Series, IEEE Photonics Society, 14-16 July 2014, Montreal, Quebec, Canada, paper # WA1.1
- N. Kinsey, M. Ferrera, G.V. Naik, *V.M. Shalaev, A. Boltasseva*, "Practical Plasmonic Devices with TiN and TCOs," 2014 Gordon Research Conference on Plasmonics, Sunday River Resort, Newry, Maine, USA, July 6-11, 2014
- (Invited) *A. Boltasseva,* "New Materials for Plasmonics and Metamaterials," 2014 Gordon Research Conference on Plasmonics, Sunday River Resort, Newry, Maine, USA, July 6-11, 2014
- V. E. Babicheva, N. Kinsey, G. V. Naik, M. Ferrera, A. V. Lavrinenko, *V. M. Shalaev*, *A. Boltasseva*, "Ultra-compact CMOS Compatible Plasmonic Modulator," Paper ID 1898, META'14, the 5th International Conference on Metamaterials, Photonic Crystals and Plasmonics, Singapore, May 20-23, 2014
- (Invited) N. Kinsey, M. Ferrera, G. V. Naik, A. Kildishev, *A. Boltasseva, V. M. Shalaev*, "New TiN-based metamaterials," META'14, the 5th International Conference on Metamaterials, Photonic Crystals and Plasmonics, Singapore, May 20-23, 2014
- (Invited) *A. Boltasseva,* ''Plasmonics and Optical Metamaterials: Going Practical with Transition Metal Nitrides,'' MRS Spring Meeting, paper number *KK2.06, San Francisco, California, USA, April 21-25, 2014
- V. E. Babicheva, N. Kinsey, G. V. Naik, M. Ferrera, A. V. Lavrinenko, *V. M. Shalaev, A. Boltasseva*, "Ultra-compact modulators using novel CMOS-compatible plasmonic materials," paper #9133-29, SPIE Photonics Europe 2014, Brussels, Belgium, April 14-17, 2014
- U. Guler, W. Li N. Kinsey, G. Naik, *A. Boltasseva*, J. Guan, A. Kildishev, *V. Shalaev*, "Plasmonic Titanium Nitride Nanostructures for Perfect Absorbers," ID: 1780265, Proceedings of Optical Nanostructures and Advanced Materials for Photovoltaics (PV), Renewable Energy and the Environment, Tucson, Arizona, USA, November 3-6, 2013
- (Invited) *A. Boltasseva*, ''Semiconductors and Ceramics: Developing New Material Platforms for Plasmonic and Metamaterial Devices,'' Fundamental optical processes in semiconductors (FOPS)-2013, Kodiak Island, Alaska, USA, August 12-16, 2013

- (Invited) *E. Narimanov*, "Natural hyperbolic materials: spatial dispersion and related phenomena", paper 8806-6, SPIE Optics and Photonics, San Diego, August 25-29, 2013
- (Invited) *A. Boltasseva*, ''Empowering Plasmonics and Metamaterials Technology with New Material Platforms,'' Frontiers of Nonlinear Physics (FNP'13), Nizhny Novgorod-Tchaikovsky, Russia, July 28-August 2, 2013
- B. Saha, G. V. Naik, S. Saber, J. Liu, J. Irudayaraj, E. Stach, *V. M. Shalaev, A. Boltasseva*, T. D. Sands, "TiN/(Al,Sc)N Metal/Dielectric Superlattices for Metamaterial Applications in the Visible Range," 55th Electronic Materials Conference (EMC), contribution J6, University of Notre Dame, South Bend, Indiana, USA, June 26-28, 2013
- G. V. Naik, B. Saha, J. Liu, S. Saber, E. Stach, T. D. Sands, *V. Shalaev, A. Boltasseva*, ''A Titanium Nitride based Metamaterial for Applications in the Visible,'' contribution QTu3A.7, CLEO/QELS 2013, San Jose, CA, USA, June 9-14, 2013
- U. Guler, J. Ndukaife, G. V. Naik, A. G. Agwu Nnanna, A. Kildishev, *V. Shalaev, A. Boltasseva*, ''Local heating with titanium nitride nanoparticles,'' contribution QTu1A.2, CLEO/QELS 2013, San Jose, CA, USA, June 9-14, 2013
- Yu. A. Barnakov, D. A. Adnew, T. Tumkur, V. I. Gavrilenko, C. E. Bonner, *E. E. Narimanov*, M. A. Noginov, "Control of wetting with hyperbolic metamaterials and metallic films", in CLEO: 2013 (Optical Society of America, Washington, DC, 2013), presentation number QTu2A.3.
- (Award talk) *A. Boltasseva*, ''Empowering Plasmonics and Metamaterials Technology with New Material Platforms,'' Materials Research Society (MRS) Spring meeting, MRS Outstanding Young Investigator Award talk, San Francisco, CA, USA, April 1-5, 2013
- (Keynote) *A. Boltasseva*, ''Plasmonic and optical metamaterial devices: Beyond gold and silver'', Meta'13, the 4th International Conference on Metamaterials, Photonic Crystals, and Plasmonics, Sharjah, UAE, March 18-22, 2013
- (Invited) M. D. Thoreson, P. R. West, G. V. Naik, N. K. Emani, and *A. Boltasseva*, "New materials and processes for plasmonic and metamaterial devices," Paper#8619-23, SPIE Photonics West, San Francisco, CA, USA, February 2-7, 2013
- G. V. Naik, B. Saha, T. D. Sands, *A. Boltasseva*, ''A titanium nitride based metamaterial for applications in the visible wavelength range,'' 4th International Topical Meeting on Nanophotonics and Metamaterials (NANOMETA 2013), Seefeld, Austria, January 2-6, 2013
- U. Guler, G. Naik, *A. Boltasseva*, *V. Shalaev*, A. Kildishev, ''Nitrides as alternative materials for localized surface plasmon applications,'' FTh4A.2, 2012 Frontiers in Optics (FiO/LS) meeting, Rochester, New York, October 14-18, 2012
- (Plenary) *A. Boltasseva*, ''Plasmonic metamaterials: Looking beyond gold and silver'', 6th International Congress on Advanced Electromagnetic Materials in Microwaves and Optics: Metamaterials 2012, St. Petersburg, Russia, September 17-22, 2012
- (Invited) *A. Boltasseva*, ''Plasmonic metamaterials: Beyond noble metals'', SPIE Optics and Photonics, contribution # 8455-80, San Diego, California, USA, August 12-16, 2012
- T. U. Tumkur, Lei Gu, J. K. Kitur, *E. E. Narimanov*, M. A. Noginov, "Enhancing absorption using metamaterials with hyperbolic dispersion", SPIE Optics & Photonics, 12-16 August, 2012, San Diego, CA, paper # 8455-22

- T. U. Tumkur, J. K. Kitur, L. Gu, B. Chu, *E. E. Narimanov*, M. A. Noginov, “Control of reflectance and transmittance in hyperbolic metamaterials with scatterers and curvilinear geometries”, SPIE Optics & Photonics, 12-16 August, 2012, San Diego, CA, paper # 8455-06
- *E. Narimanov* and I. Smolyaninov, "Thermal hyper-conductivity: beyond Stefan-Boltzmann law", paper 8488-05, SPIE Optics and Photonics - 2012, San Diego, August 12 - 16, 2012
- (Invited) *A. Boltasseva*, “Oxides and nitrides as alternative plasmonic materials in the optical range,” Gordon conference on Plasmonics, Colby College, Waterville, Maine, June 10-15, 2012
- G. Naik, J. Schroeder, U. Guler, X. Ni, A. Kildishev, T. Sands, *A. Boltasseva*, “Metal nitrides for plasmonic applications,” CLEO/QELS 2012 Proceedings, QW3H.4, 2 pages CLEO/QELS 2012, San Jose, CA, USA, May 6-11, 2012
- (Invited) *A. Boltasseva*, “Oxides and nitrides as plasmonic materials,” 3rd International Conference on Metamaterials and Photonic Crystals, META'12, Paris, France, April 19-22, 2012
- (Invited) *A. Boltasseva*, “Improved material building blocks for metamaterials,” International Workshop on Electromagnetic Metamaterials (IWEM-V), Albuquerque, New Mexico, USA, March 26-27, 2012
- (Invited) G. V. Naik, J. Kim, P. R. West, N. K. Emani, *A. Boltasseva*, “The road ahead for metamaterials and plasmonics: Improved material building blocks,” Physics of Quantum Electronics, Snowbird, Utah, USA, January 2-7, 2012

(5.3) Awards

2014 Member of the Purdue Innovator Hall of Fame, Purdue Research Foundation, Purdue University *(Boltasseva, Shalaev)*

2014 Joseph W. Goodman Book Writing Award for the book Optical Metamaterials: Fundamentals and Applications; authors: W. Cai and V. Shalaev *(Shalaev)*

2014 University Faculty Scholar, College of Engineering, Purdue University *(Boltasseva)*

2014 SPIE travel grant, SPIE Optics and Photonics, San Diego, CA, August 16-21, 2014 *(Naresh Emani, Boltasseva’s graduate student)*

2013 Materials Research Society (MRS) Outstanding Young Investigator Award *(Boltasseva)*

2013 Institute of Electrical and Electronics Engineers (IEEE) Photonics Society Young Investigator Award *(Boltasseva)*

2013 IEEE Photonics Society (IPS) 2013 Graduate Student Fellowship *(Gururaj Naik, Boltasseva’s graduate student)*

2013 Outstanding Graduate Student Research Award, College of Engineering, Purdue University *(Gururaj Naik, Boltasseva’s graduate student)*

2012 Nanotechnology Award from UNESCO *(Shalaev)*

2012 National Academy of Engineering (NAE) U.S. Frontiers of Engineering (FOE) Symposium invitation, September 13-15, 2012, GM Technical Center, Warren, Michigan, USA (invitation-only symposium gathering 78 outstanding engineers under the age of 45) *(Boltasseva)*

2012 Purdue College of Engineering Early Career Research Award (for ‘early excellence with clear potential for future preeminence in research’) *(Boltasseva)*

(5.4) Selected Invited seminars

Boltasseva:
- Applied Physics, Yale University (January 2015)
- Institute for Nanoscale Science and Engineering, Vanderbilt University (January 2015)
- Indiana University-Purdue University Indianapolis (January, 2015)
- Technion-Israel Institute Of Technology, Haifa, Israel (October 2013)
- University of California, Berkeley, CA, USA (June 2013)
- Kirensky Institute of Physics, Krasnoyarsk, Russia (February 2013)
- Moscow Institute of Physics and Technology, Moscow, Russia (February 2013)
- Russian Quantum Center, Moscow, Russia (February 2013)
- Lebedev Physical Institute, Russian Academy of Sciences, Russia (February 2013)
- Geballe Laboratory for Advanced Materials, Stanford University (February 2013)
- Technical University of Denmark, Denmark (April 2012)

Shalaev:
- Raytheon, Los Angeles, CA, November 12, 2013
- Technion, Haifa, Israel, October 16, 2013
- St. Petersburg ITMO, Russia, September 26, 2013
- AMOLF, Amsterdam, The Netherlands, September 23, 2013
- MITRE Corporation, JASON Program, McLean, VA, April 27-28, 2012
- UC Berkeley, April 11, 2012
- Skolkovo, Russia, Days of Quantum Physics, December, 2012
- Russian Quntum Center, Moscow, Russia, December, 2012

Narimanov:
- École Polytechnique de Montréal, July 17, 2014
- University of Notre-Dame, March 21, 2014
- Imperial College London, April 17, 2013